AD-A231 087

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. Agency Use Only (*Leave blank*).

2. Report Date.
1990

3. Report Type and Dates Covered.
Journal Article

4. Title and Subtitle.
Characteristics of Circulation in an Indonesian Archipelago Strait from Hydrography, Current Measurements and Modeling Results

5. Funding Numbers.
Program Element No. 61153N
Project No.
Task No.
Accession No. DN496442

6. Author(s).
Stephen P. Murray, Dharma Arief, John C. Kindle, and Harley E. Hurlburt and W. A. Kuperman

7. Performing Organization Name(s) and Address(es).
Ocean Sciences Directorate
Naval Oceanographic and Atmospheric Research Laboratory
Stennis Space Center, MS 39529-5004

8. Performing Organization Report Number.
JA 323:018:90

9. Sponsoring/Monitoring Agency Name(s) and Address(es).
Ocean Sciences Directorate
Naval Oceanographic and Atmospheric Research Laboratory
Stennis Space Center, MS 39529-5004

10. Sponsoring/Monitoring Agency Report Number.
JA 323:018:90

11. Supplementary Notes.
POSA

12a. Distribution/Availability Statement.
Approved for public release; distribution is unlimited.

water from sea levels
the

12b. Distribution Code.

oceanographic data.
such as

13. Abstract (*Maximum 200 words*).

The Lombok Strait, a gap in the lower Indonesian Archipelago, second in cross sectional area only to the Timor passages, provides a major pathway for the Pacific to Indian throughflow. A global reduced gravity model, corroborated by dynamic height climatology from the Generalized Digital Environmental Model, predicts annual mean sea levels 15-20 cm higher at the Pacific Ocean entrance to the Indonesian Seas than in the Indian Ocean south of the archipelago straits. Consistent with this regional pressure gradient, Pacific core layers of the Northern Subtropical Central Water and the North Pacific Intermediate Water are traced southward from the Makassar Strait into the Lombok Strait. Maps of temperature, salinity, and density distributions and sea surface dynamic heights in the Lombok Strait from January, June, and September 1985, also indicate a persistent southward flow of appreciable magnitude. Geostropyhic speeds, however, are clearly too large by a factor of two or more. Current meter arrays in the north strait (January 1985 - March 1986) provide direct measurements of southward currents which persist through most of the year and are concentrated in the upper few hundred meters, consistent with Wyrtki's (1987) analysis of the regional pressure gradient. Maximum sustained speeds of over 70 cm/sec occur from July to September with a long period of weak currents from mid-October 1985 through January 1986. Tropical cyclones in the Timor Sea (December-April) force strong northward flow reversals, which can persist for ten days. The wind-forced numerical model identifies the strong westward wind stresses in the Timor Sea during the southeast monsoon as the major cause of the annual cycle of current in the Strait.

14. Subject Terms.
(U) Indian Ocean; (U) Somali Current; (U) Equatorial Dynamics

15. Number of Pages.
21

16. Price Code.

17. Security Classification of Report.	18. Security Classification of This Page.	19. Security Classification of Abstract.	20. Limitation of Abstract.
Unclassified	Unclassified	Unclassified	SAR

CHARACTERISTICS OF CIRCULATION IN AN INDONESIAN ARCHIPELAGO STRAIT FROM HYDROGRAPHY, CURRENT MEASUREMENTS AND MODELING RESULTS

Stephen P. Murray and Dharma Arief
Coastal Studies Institute
Louisiana State University
Baton Rouge, Louisiana 70803-7527

John C. Kindle and Harley E. Hurlburt
Naval Oceanographic Research and
Development Activity
Code 323
Bay St. Louis, Mississippi 39529

ABSTRACT. The Lombok Strait, a gap in the lower Indonesian Archipelago second in cross sectional area only to the Timor passages, provides a major pathway for the Pacific to Indian throughflow. A global reduced gravity model, corroborated by dynamic height climatology from the Generalized Digital Environmental Model, predicts annual mean sea levels 15-20 cm higher at the Pacific entrance to the Indonesian Seas than in the Indian Ocean south of the archipelago straits. Consistent with this regional pressure gradient, Pacific core layers of the Northern Subtropical Central Water and the North Pacific Intermediate Water are traced southward from the Makassar Strait into the Lombok Strait. Maps of temperature, salinity, and density distributions and sea surface dynamic heights in the Lombok Strait from January, June, and September 1985 also indicate a persistent southward flow of appreciable magnitude. Geostrophic speeds, however, are clearly too large by a factor of two or more. Current meter arrays in the north strait (January 1985 - March 1986) provide direct measurements of southward currents which persist through most of the year and are concentrated in the upper few hundred meters consistent with Wyrtki's (1987) analysis of the regional pressure gradient. Maximum sustained speeds of over 70 cm/sec occur from July to September with a long period of weak currents from mid-October 1985 through January 1986. Tropical cyclones in the Timor Sea (December-April) force strong northward flow reversals which can persist for ten days. The wind-forced numerical model identifies the strong westward wind stresses in the Timor Sea during the southeast monsoon as the major cause of the annual cycle of current in the Strait.

L. J. Pratt (ed.), The Physical Oceanography of Sea Straits, 3–23.

1. Introduction

Recent research on sea straits emphasizes the variability of forcing mechanisms that control the circulation in many of the major sea straits around the world. For example, we note the dominant role of evaporation-induced pressure gradients in the Mediterranean and Middle East straits (Bryden and Stommel, 1984), the inertial effect of the Gulf Stream in the Florida Strait (Lee et al., 1985), the cross-stream geostrophically induced surface slope of a major western boundary current driving the flow in the Tsugaru Strait (Conlon, 1981), and the role of large scale meteorological forcing in the Strait of Belle Isle (Garrett and Petrie, 1981).

From another point of view, sea straits are the systematic result of large-scale geophysical and tectonic processes and often cluster in environmental regions that impose similar dynamical constraints on members of the cluster. A notable example is the Bab El Mandeb/Hormus/Tiran/Gibraltar cluster, where the low-frequency circulation is dominated by the effects of regional evaporation. The island arcs that rim subduction zones are a prominent feature of plate margin tectonics, and the characteristic breaches in these arcs have evolved into important sea straits. The Indonesian archipelago (Figure 1), containing the Sunda/Malaka/Makassar/Lombok/Timor straits is another critical cluster that provides the only connection between ocean basins in tropical latitudes. The potential importance to the global circulation of the net transport (the Indonesian throughflow) between the Pacific and Indian Oceans through these straits is now well recognized (Gordon, 1986). Pacific Ocean, South China Sea and Java Sea waters are of significantly lower salinity and higher temperature than the adjacent Indian Ocean. Potential inter-basin fluxes of these properties appear critical to the heat and salt balances in the Indian Ocean (Toole and Raymer, 1985).

Despite numerous breaches in the archipelago, the deep passages (2,000 m depth) bracketing Timor were considered (Wyrtki, 1961) the sole pathways for any significant transport into the Indian Ocean. In terms of cross-sectional area available for transport, the second most important channel through the lower archipelago is the Lombok Strait between the island of Bali and Lombok (Figure 1). Lying at the end of a deep bathymetric trough linking it to the Makassar Strait, it provides a direct conduit for Pacific Ocean water into the Indian Ocean. Depths in the Lombok Strait are typically 800-1,000 m except at the south end where a small island Nusa Penida divides the channel. The western channel (Badung Strait) has a cross sectional area less than one-fourth that of the main channel between Nusa Penida and Lombok Islands. An extremely irregular sill with maximal depths of about 300 m connects Nusa Penida to Lombok Island.

The objectives of this paper are to present both: (a) a general review of observational data taken in the Lombok Strait area during 1985-1986; and (b) the present status of our understanding of the forces controlling the low-frequency circulation in the strait, interpreted mainly from numerical model results. These results not only shed considerable light on the dynamics controlling the circulation through

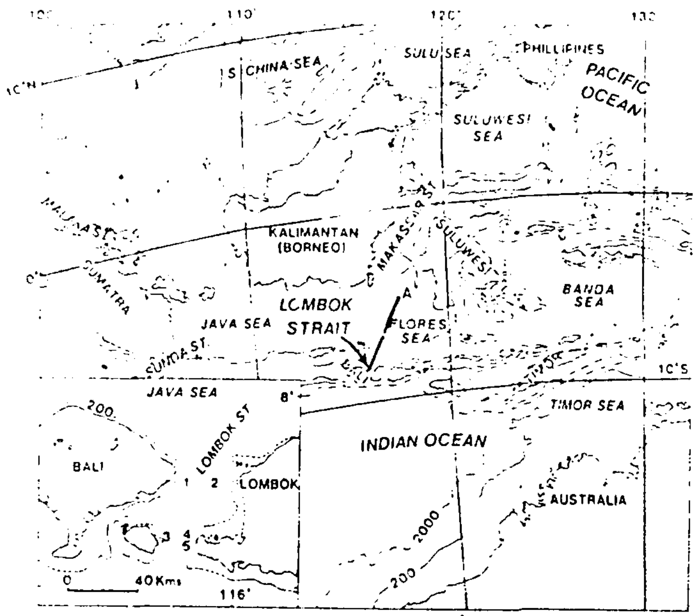

Figure 1. Regional map showing the location of the Lombok Strait with an inset showing current meter mooring locations in the Strait.

this particular strait, but also provide a general framework for understanding transport and fluctuations in the other straits of the archipelago.

2. Observations and Model

Field work and data collection were conducted from January 1985 to March 1986. Seven current moorings were deployed, five in the Lombok Strait (see Figure 1) and two in the bathymetric trough (in the western Flores Sea) linking the Makassar Strait outflow to the Lombok Strait. More than 120 current meter months of data were collected. A total of 234 CTD casts were taken in the Lombok Strait, its Indian Ocean approaches, and the western Flores Sea extending as far north as the Makassar Strait and east into the Flores Sea to 119°E. The CTD station grid occupied with some variations in January, June, and September 1985 is shown in Figure 2. Thirty-four meter months of sea level (pressure gauge) data taken in the Strait and at the Makassar trough mooring site will be discussed separately. Data on the regional sea level during our observations were collected from tide gauges in the Philippines and northwest Australia courtesy of Klaus Wyrtki, University of Hawaii, and the Flinders Tidal Observatory, Australia.

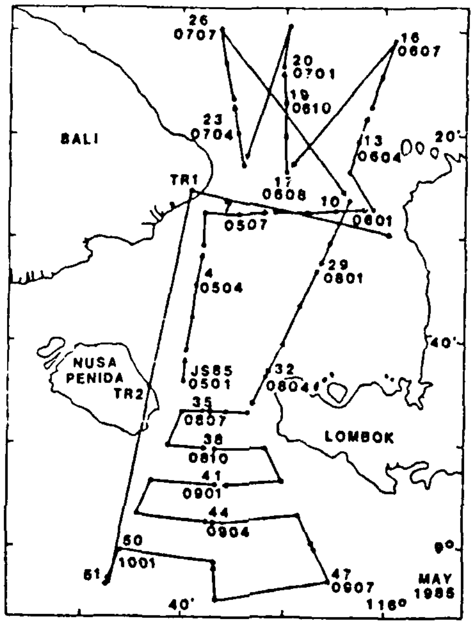

Figure 2. The basic CTD grid occupied in January, June, and September, 1985.

To examine the mean and seasonal variability of the throughflow in the Indonesian passages and the forcing mechanisms responsible for the variability, we use the most recent version of the NORDA Global Model, forced by monthly averages of the European Centre for Medium-Range Weather Forecasts (ECMWF) 1,000-mb winds.

This model is a multi-layer, primitive equation formulation which incorporates a free surface, arbitrary coastline geometry, full scale bottom topography in the lowest layer and a semi-implicit time scheme. The model equations are formulated in spherical geometry over a latitudinal extent ranging from 71°N to 72°S. Lateral boundaries are located at the 200 m contour using bathymetric data from the Synthetic Bathymetric Profiling Systems (SYNBAPS) data base. The walls are rigid and the no-slip condition is prescribed on the tangential flow.

The simulations described in this paper use a one active layer reduced gravity version of the model which includes the effects of mixing and mean thermodynamics. Density gradients within the upper layer are permitted and are modified by horizontal advection, entrainment, eddy diffusion and relaxation to a mean density climatology based on Levitus (1982). The relaxation time constant is a function of layer depth and ranges from three months for a 50 m thick layer to 1.5 years for a layer of 550 m. Except for very shallow layers, the relaxation does not produce a strong constraint on the model density field. Entrainment from the lower layer is initiated when the layer

thickness reaches a minimum value, mass is conserved through uniform detrainment. The model formulation permits the specification of surface heat fluxes, but that option was not utilized in these simulations. A list of model parameters is given in Table 1. Also see Kindle et al (1989).

TABLE 1

PARAMETER	DESCRIPTION	VALUE
A(m)	Horizontal eddy viscosity (momentum)	1500 m^2/sec
A(d)	Horizontal eddy viscosity (density)	5000 m^2/sec
g	Gravity	9.8 m/sec^2
dx	Grid spacing in longitude	7 deg dy
dy	Grid spacing in latitude	.5 deg
dt	Time step	60 min.
H	Initial layer depth	250 m
hm	Maximum layer thickness for which mixing is initiated	60 m

3. Regional Forcing

The Indonesian Seas lie at the western edge of the Pacific trade wind belt where the persistent westerly directed wind stresses pile water up against the boundary. As a result, annual mean sea-surface elevations are as much as 20 cm higher at the Pacific entrances to the archipelago south of the Philippines than in the Indian Ocean south of Java. This pattern is seen clearly in our model results in Figure 3, where the average sea-surface deviations from the initial state over the two-year period 1984 through 1985 are presented. The long-term average climatology of sea surface dynamic height from the Generalized Digital Environmental Model (GDEM) data set referenced to 1,000 db (Figure 4) shows a markedly similar pattern.

In addition to trade wind forcing of mean annual sea-level differences across the archipelago, it is well known that the Asian monsoon drives a strong seasonal cycle of meteorological forcing over the Indonesian Seas (Wyrtki, 1961). The southeast Asian monsoon brings strong east winds across the archipelago from May to early September and west winds from November to March. Transition periods are characterized

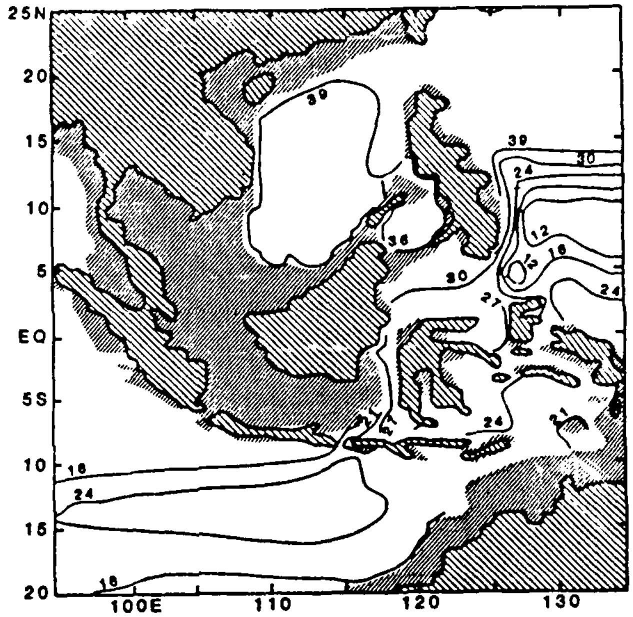

Figure 3. Mean sea surface deviations (cm) from the initial state of the reduced gravity model for the two-year period 1984-1985.

by weak, variable winds. Wyrtki (1961) has shown the step-like reversals of the monsoon dominate the surface circulation along the Java Sea - Banda Sea axis.

4. Thermohaline Characteristics

The general characteristics of the vertical structure of temperature and salinity in the region are illustrated in Figure 5 from a CTD cast taken in the north Strait. Surface isothermal and isohaline layers usually 30-50 m thick overlay a strong thermocline extending to about 400 m below which the temperature decreases slowly to 4°C. The low salinity in the surface layer reflects the regionally intense rainfall. A salinity maximum and a salinity minimum occur near 150 m and 300 m, respectively.

The presence of Pacific Ocean core water in the Indonesian Seas was documented by Wyrtki (1961) from historical data widely spaced in time and space. Our CTD transect from the southern end of the Makassar Strait 475 km south through the Lombok Strait distinctly shows (Figure 6) the salinity maximum of the core layer of the Northern Subtropical Central Water (NSCW) at 150 m ± 25 m, in early June 1985. There is no appreciable change in the salinity maximum over this distance until

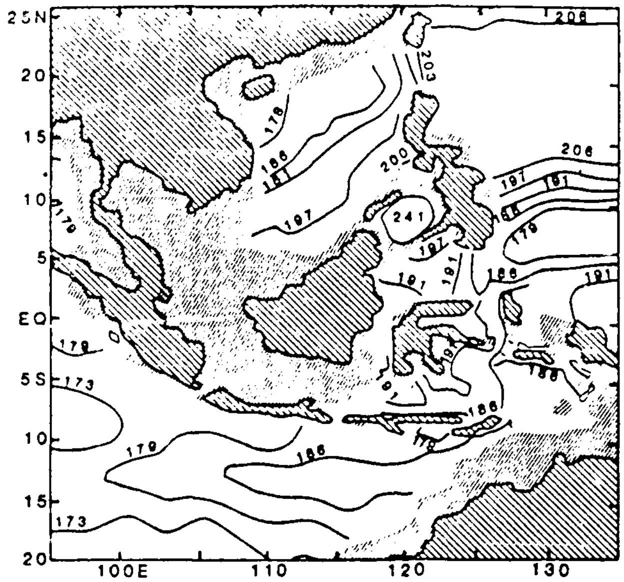

Figure 4. Dynamic height (dyn. cm) from the long-term GDEM climatology.

encountering intensified mixing in the Lombok Strait. Similarly, the salinity minimum diagnostic of the North Pacific Intermediate Water (NPIW) is tracked in this figure from the Makassar Strait across the Flores Sea with little change until reaching the Lombok Strait.

The Pacific Ocean core layers penetrate into the Lombok Strait in all three months we observed. As shown in Figure 7, there was considerable seasonal variability in the NSCW. A much stronger and more extensive salinity maximum occurred in September than did in June. The NPIW core layer, on the other hand, showed no discernible seasonal variability. The NSCW salinity maximum core layer at 150 m depth clearly survived mixing over the sill only in the September data when it penetrated only about 25 km into the Indian Ocean. Patches of NPIW water were occasionally found south of the sill, apparently brought up over the sill by Bernoulli suction (Bryden and Stommel, 1984; Kinder and Parrilla, 1987). It is notable that these core layers, having travelled thousands of kilometers from their Pacific origin, are destroyed by locally intense mixing in the Lombok Strait.

The distribution of thermohaline properties in the surface layer in the Strait reflect the southward motion indicated by the core layers. Salinity, temperature, and density distributions on the 10 db surface are shown in Figure 8a from early June 1985. The isotherms clearly show the penetration of the warm (29°C) surface isothermal layer into the north Strait with very little temperature change along the axis of the strait until encountering the sill. South of the sill an extremely

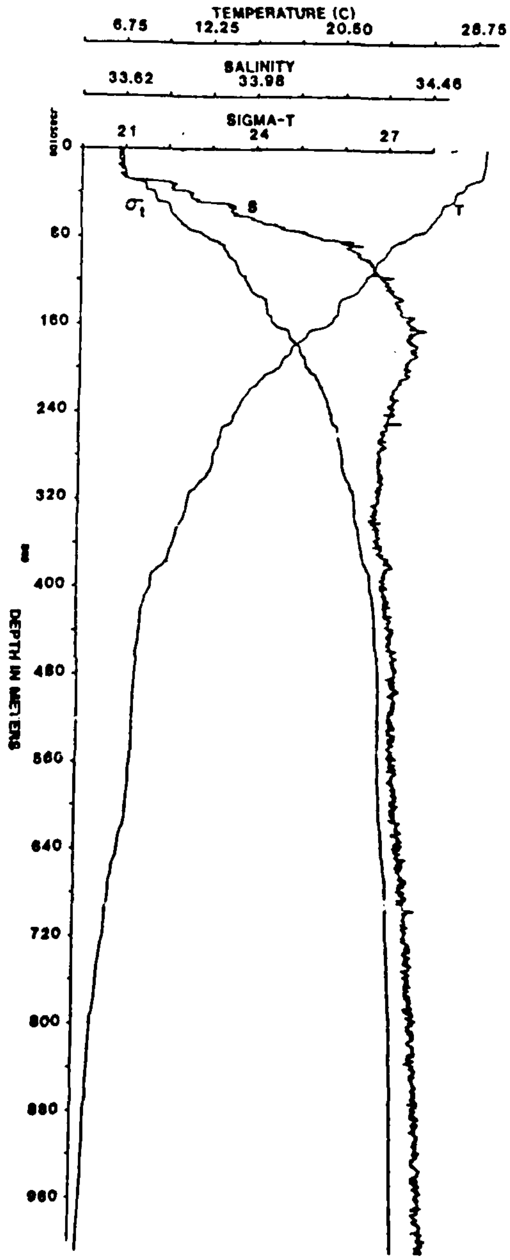

Figure 5. An example of a CTD cast from the north Lombok Strait showing the well-mixed surface layer and the salinity maximum and minimum core layers in the thermocline.

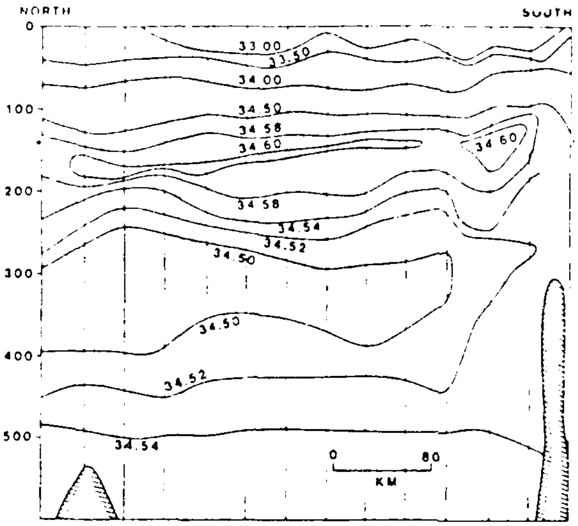

Figure 6. Vertical section of salinity from the southern end of the Makassar Strait to the sill at the southern end of Lombok Strait along the line labelled A in Figure 1.

well-developed thermal plume intrudes over 30 km into the Indian Ocean. Temperature gradients are steepest on the western side of the plume (over 3° drop in 15 km) suggesting the presence of the eastward directed Java Coastal Current which runs at high velocities along the south coast of the archipelago from December to June (Wyrtki, 1961).

The salinity distribution (Figure 8b) on the 10 db surface shows a similar but less dramatic evolution from north to south in the Strait. Low salinity coastal boundary layer waters originating from Javanese rivers enter the Strait from the northwest to combine with higher salinity water from the Flores Sea. Salinities at 10 db gradually increase to the south of the sill. A haline plume penetrates into the Indian Ocean and deflects to the east as a result, we believe, of impacting the Java Coastal Current.

The density distribution (Figure 8c) on the 10 db surface nicely summarizes the southward increased mixing of homogeneous, warm, less saline water above 10 db with the cold, saltier water below. The penetration of the density plume, with a front-like western limb and an eastward deflection are also all present in the density field.

The dynamic topography of the sea surface shown in Figure 9 also adds important information on the flow pattern in the Strait. Wyrtki (1987, 1961) has shown that most of the pressure gradient in this region is contained in the upper 200 m and thus we choose 500 db as a suitable reference level. In January there is a 15 dyn. cm gradient across the mid-section of the Strait indicating a substantial surface layer flow to

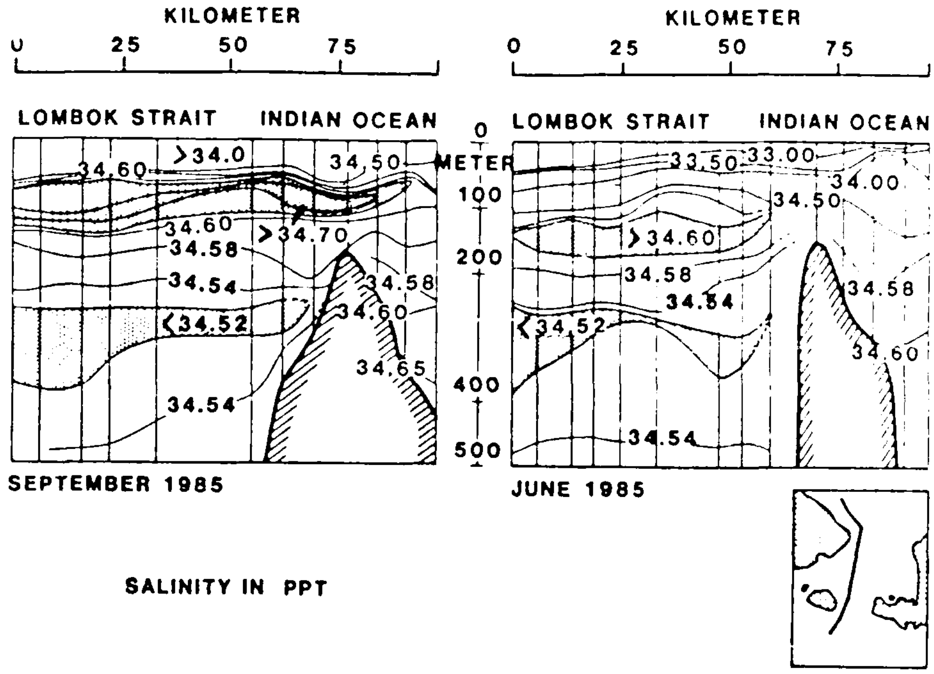

Figure 7. Vertical sections of salinity in September and June 1985 along the west side of the Lombok Strait showing the location of NSCW and NPIW core layers.

the south. The dynamic height contours fan out radially into the Indian Ocean, but they are skewed to the southeast reflecting the direction of movement indicated by the haline and thermal plumes. Unfortunately, equipment failure in January did not allow measurements at the CTD stations in the northern approaches. In the September map of surface dynamic height (0/500 db), a similar surface slope exists across the mid-section of the Strait with a strong southward flow indicated. Additionally, these dynamic height data show a 10-15 cm drop in the sea surface along the center line of the strait from the west Flores Sea inflow region in the north to the Indian Ocean outflow region in the south. The internal radius of deformation of the Strait is 120 km, much larger than the width of the Strait. Therefore a geostrophic balance is not expected either across or along the Strait. In fact, geostrophic surface layer speeds indicated by the cross strait slopes are over 300 cm/sec. Such unrealistically high speeds suggest a more complex across-strait momentum balance for such low latitude straits. Quantitative knowledge of the current field must come from direct observations.

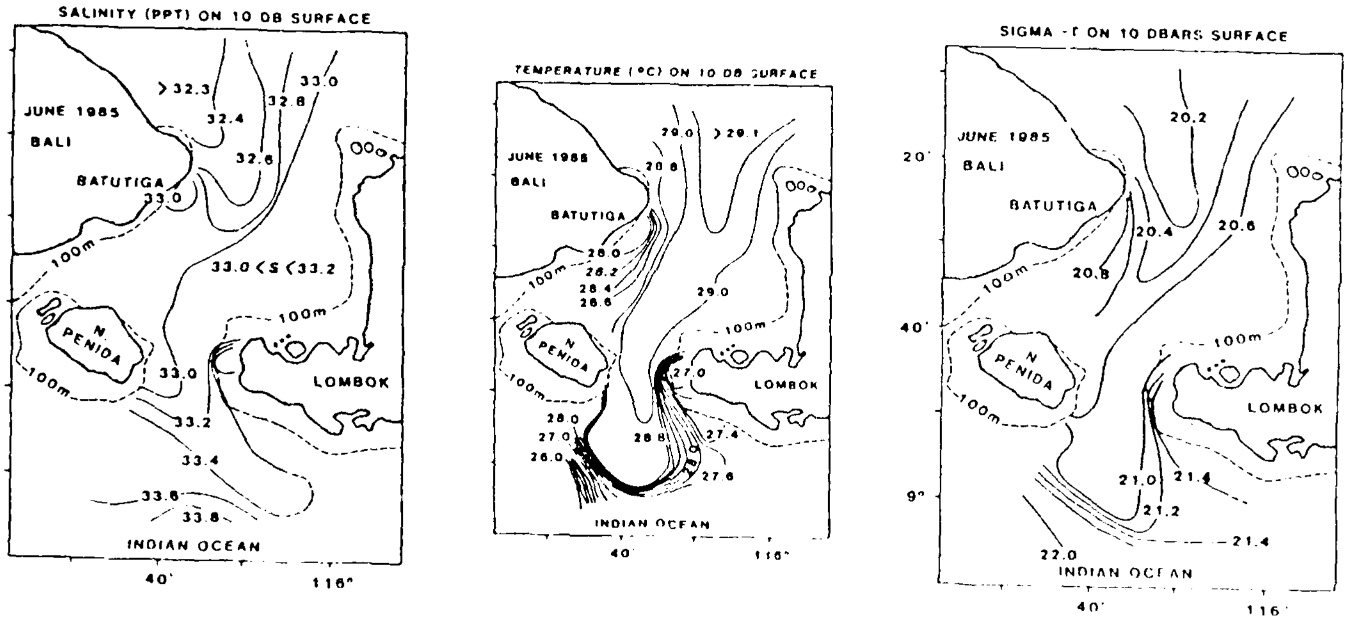

Figure 8. Salinity (A), temperature (B), and density (C) on the 10db surface, June 1985.

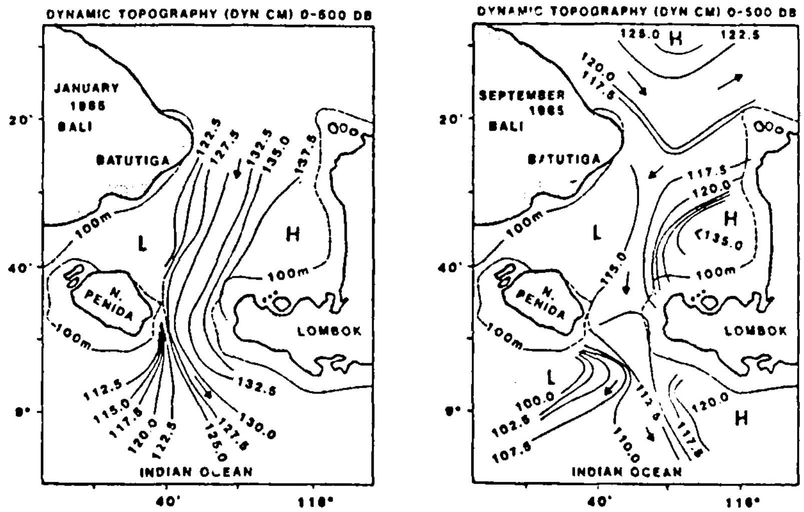

Figure 9. Dynamic topography of the sea surface in January and September 1985.

5. Currents

The annual mean north-south surface slope across the Indonesian Seas (Figures 1 and 2) and the thermohaline properties (Figures 7 through 9) suggest the presence of a persistent southward flow through the Lombok Strait. Wyrtki's (1987) analysis of the regional pressure field indicates such a transport should be concentrated in the upper 200 m. In Figure 10 examples of our observations of currents at four levels in the north Strait from January to May 1985 document the presence of a very strong and persistent southward flow in at least the upper 100 m. This southward mean flow is also present at the 300 m level, but with a magnitude of only 3-5 cm/sec. Dramatic flow reversals to the north reaching 75 cm/sec at the 35 m level interrupt the persistent southward transport. The period February 15 to March 15, as well as the last ten days of April 1985, is dominated by reversal events.

A 13-month time series of currents at the 35 m level at the Site 2 mooring (Figure 11) shows the southward transport reaches sustained maxima of over 70 cm/sec in July, August and September. Deceleration occurs abruptly in mid-October and then begins a long period of weak flow extending into early January 1986. The current meter data principally from Sites 1 and 2 were binned into monthly block averages and used to calculate the seasonal cycle of transport through the Strait (Murray and Arief, 1988). Monthly average transport reached maximum of 4 Sv in August with a 1985 yearly average transport of 1.8 Sv.

The current meter mooring at the sill (Site 5, Figure 1) operated only during the first deployment as tidal currents (Figure 12) were extremely rigorous. Daily maximum speeds reached nearly 300 cm/sec at

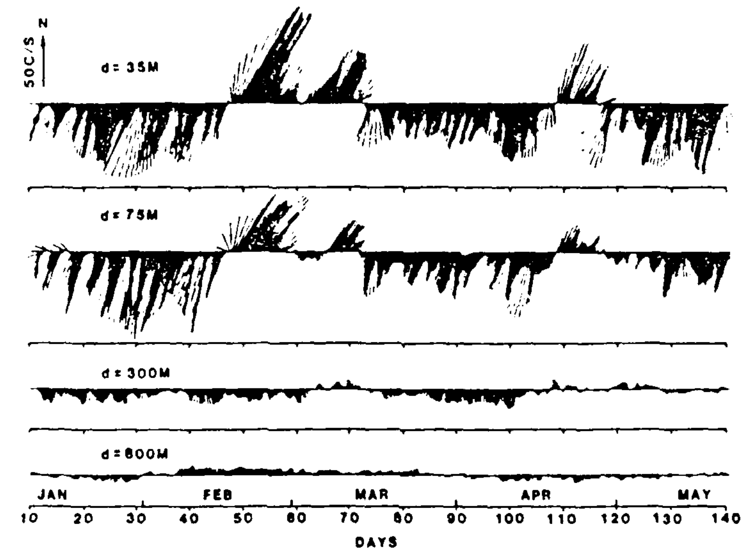

Figure 10. Current velocity vectors (60 hrs. low pass) from the four levels of the north Strait mooring at Site 2, January-May 1985.

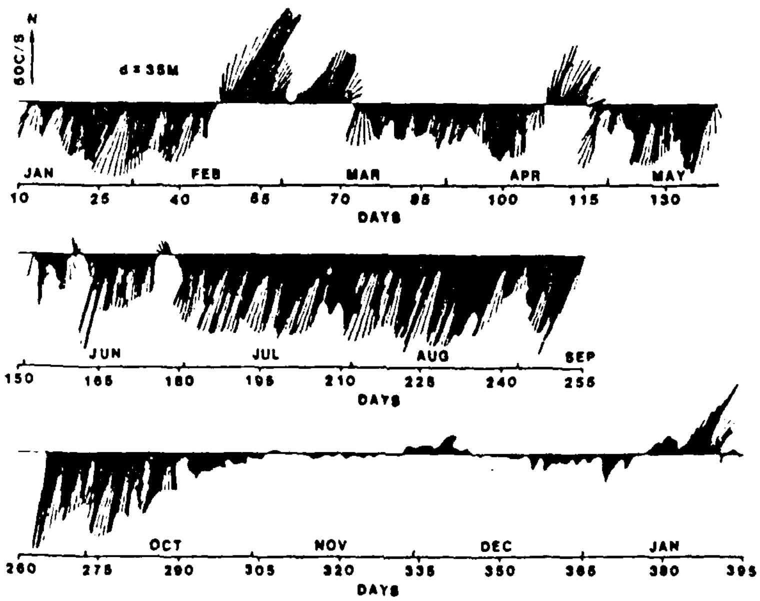

Figure 11. Thirteen-month time series of current from the 35 m level, Site 2 mooring, January 1985-January 1986.

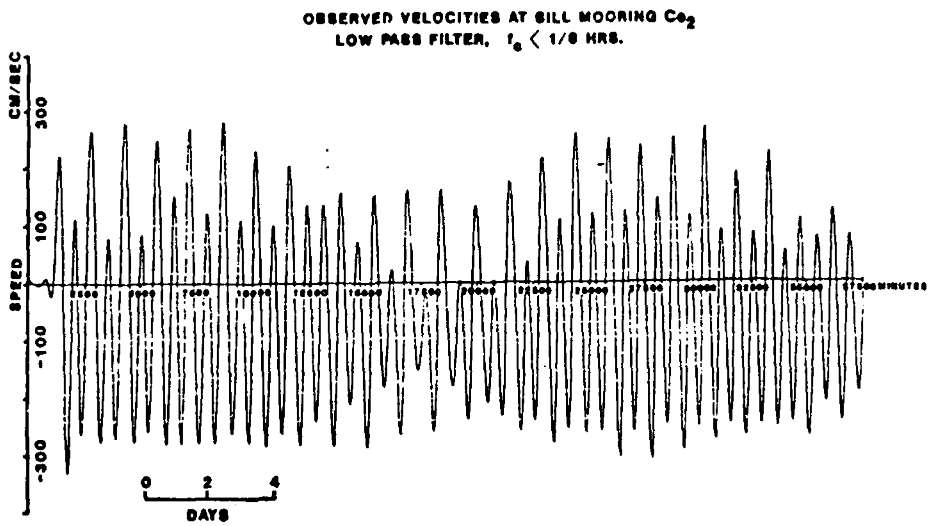

Figure 12. North-South current component (north - positive) observed at the sill mooring January 1985.

this site on the shallow (150 m) east flank of sill. The low pass data from the sill mooring mirrors that of the north strait (Figure 10), but, of course, with greater speeds.

In summary, the current meter data indicate at least three important time scales in the sub-tidal flow regime: (1) a steady southward flow apparently associated with an annual mean sea level difference between the western Pacific and the Indian Ocean; (2) a seasonal modulation of the mean flow producing maximum speeds in the months of the northern summer and minima in the late fall and winter; and (3) strong northward flow reversals occurring in January through April.

6. Northward Flow Reversals

December through April is the usual tropical cyclone season in the Timor Sea. Although their effects are well recognized on the northwest Australian coast (McBride and Keenan, 1982) to our knowledge their influence on Indonesian waters is unreported. In Figure 13 we plot the tracks of three tropical storms (Hubert, Isobel, and Jacob) transiting the Timor Sea in February 1985. The coastal waters south of Java and Lombok were under the influence of these cyclone winds for most of the latter half of February. The capability of these storms to affect the sea surface is clear from Figure 14 as the colinear positions of Hubert, Isobel, and Jacob all bring strong (35-45 knots) sustained westerly winds along the south coast of the archipelago. In fact, all other northward current reversals in the Strait occur in conjunction with

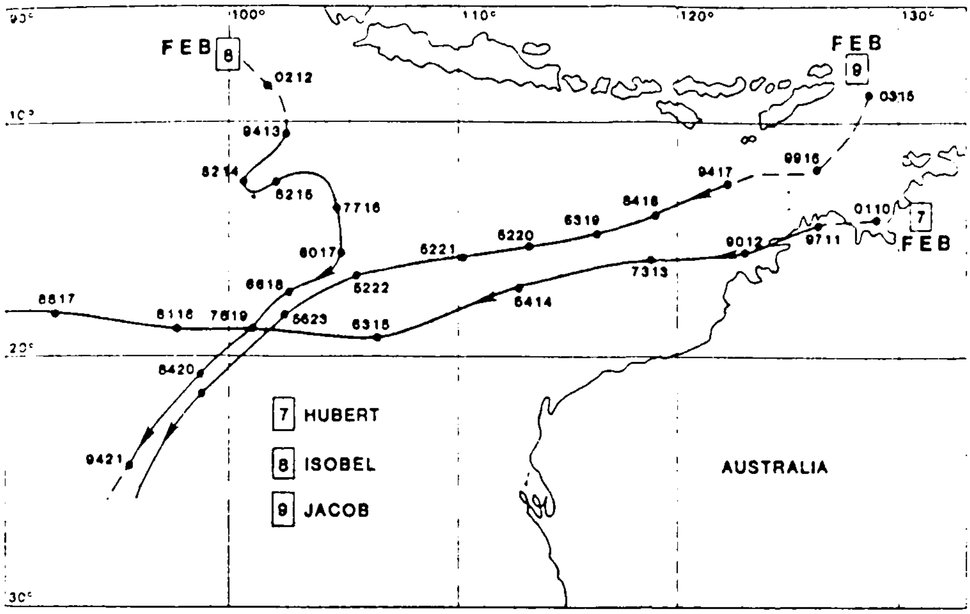

Figure 13. Tracks of three tropical cyclones in the Timor Sea in February 1985. The storm center at noon is plotted each day with the first two digits being central pressure and the second two digits the day of the month (from data in Kuuse, 1985).

Timor Sea cyclones. A set-up from the Ekman transport toward the coast of sufficient magnitude to reverse the pressure gradient along the Strait appears responsible for the flow reversal. We are pursuing this quantitatively in cooperation with the Australian Bureau of Meteorological Research using their operational Timor Sea storm surge model.

7. Numerical Simulations

Considerable insight into the forcing controlling the circulation through the Lombok Strait is gained from the results of the reduced gravity model of the region. Figure 15 shows the upper layer velocity field on May 28, 1985. Note the presence of the Mindanao Current off the southeast coast of the Philippines and the impressive scale of the Mindanao eddy in the northeast corner of the figure, all in agreement with recent observations (Lukas, 1988; Richardson and Collins, 1988). The southward flow seen in the Makassar Strait continues throughout the year in agreement with the ship drift climatology and continually shunts water into the Lombok Strait.

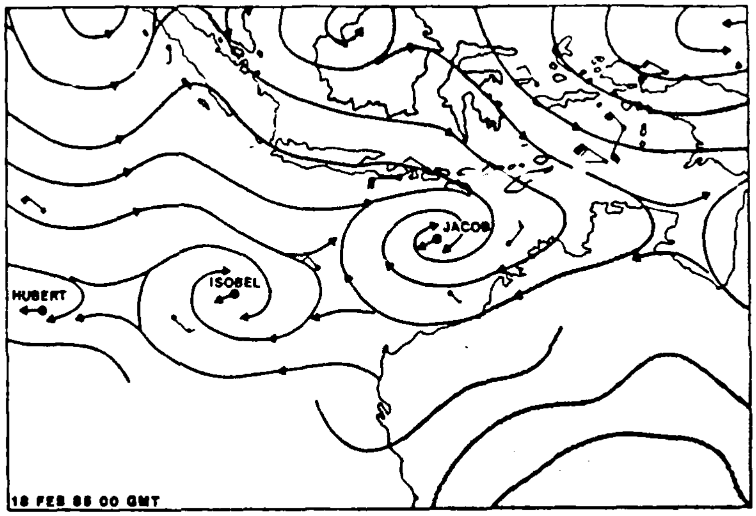

Figure 14. Sea surface streamline map in the Timor Sea for February 18, 1985 from the Singapore Meteorological Service.

A 13-month time series of low frequency transport through Lombok Strait predicted by the model is compared to our observation in Figure 16. Due to present grid limitations, the active upper layer in the model is larger by a factor of 2.2 than the cross sectional area of the Strait above 200 m where the transport is concentrated. For the first approximation we assume the model transport is directly proportional to cross-sectional area and a corrected transport scale is added to Figure 16. Monthly block averages of transport utilizing all current meter data were presented in Murray and Arief (1988). The observed transport shown in Figure 16 is calculated somewhat differently by first establishing the best fit regression relation between these monthly average transports and individual 40-hour low pass curr ~t meter time series. The data from the 35 m level instrument at Site _ provided the best predictor (R^2 = .78) of the total monthly averaged transport. The regression coefficients so determined were then used with the complete time series from the 35 m level Site 2 meter to estimate the higher temporal resolution transport seen in Figure 16. We note the general agreement between model and observations in the phase of the major seasonal pulse of southward transport. There is also good agreement in magnitude between the adjusted model transport and the observations. The distinct pulse of low southward transport in February due to intense cyclonic activity in the Timor Sea is present in both the observations and the model. Clearly the February 1985 cyclonic winds were of sufficiently large time and length scale (Figure 14) to affect the ECMWF winds driving the model, while other tropical cyclones also driving flow

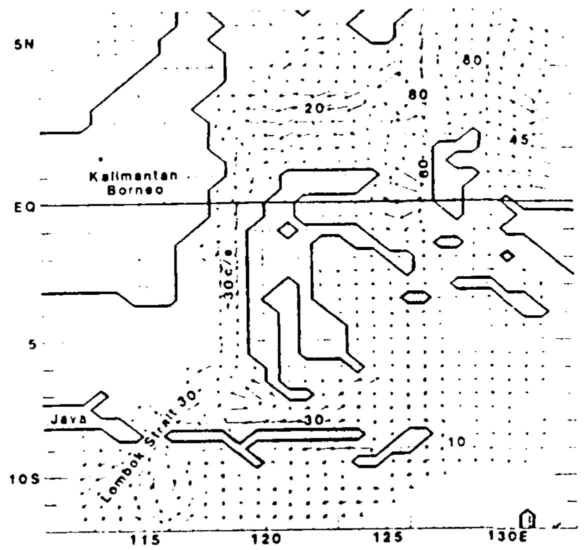

Figure 15. Velocity field from the numerical simulation of May 28, 1985. Representative current speeds (cm/sec) are shown at a few locations.

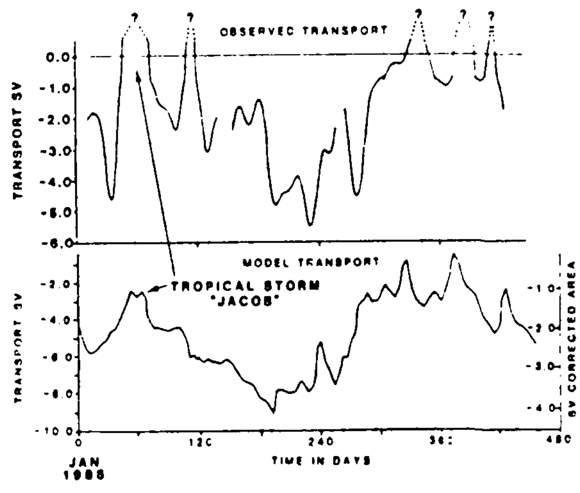

Figure 16. The transport through the Lombok Strait predicted by the model compared to the transport observed in the north strait. The right side of the lower panel is a scale corrected for excess cross-sectional area mandated by model limitations.

reversals (such as the one in late April) were not. We note the period of low transport in the observations from November 1985 to February 1986 appears to be well modeled also.

Finally, to explain the large seasonal signal in the transport we compare (Figure 17) the ECMWF observed zonal wind stress averaged over the Timor Sea and the observed sea level difference between Davao and Darwin to transport through the Strait during our period of observation. The southeast monsoon produces a large pulse of westward zonal wind stress during the months of the northern summer. The sea surface south of the archipelago is apparently depressed as a result of offshore Ekman transport which is reflected in a maximum in the Davao minus Darwin sea level difference.

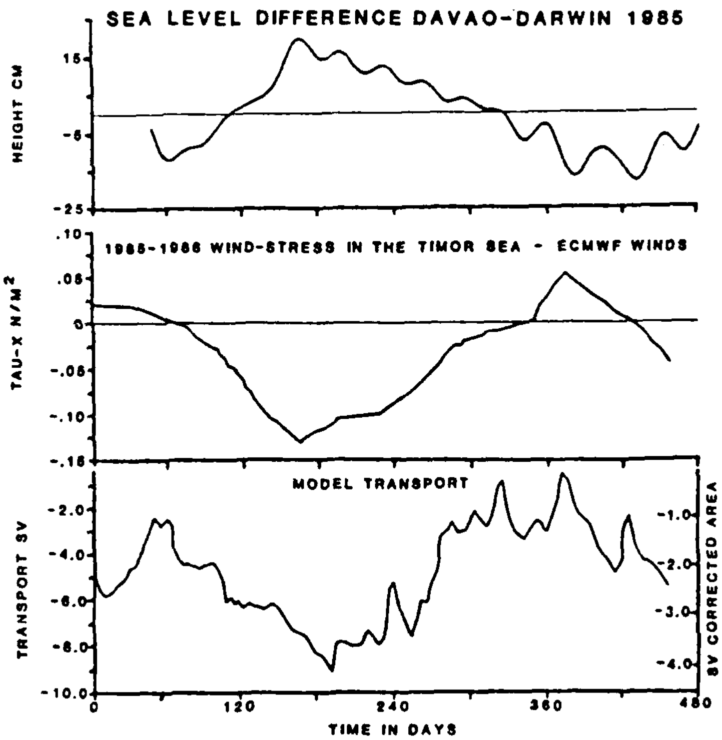

Figure 17. The model transport through the Lombok Strait compared to the average ECMWF zonal wind stress in the Timor Sea and Davao-Darwin sea level difference for the period January 1985-April 1986.

The net result is the July through September pulse of southward transport figuratively being pulled through the Lombok Strait by the

depressed sea surface to the south. Our quantitative results from the numerical simulations are in essential agreement with the throughflow mechanism advanced by Wyrtki (1987). The model simulations also suggest that the high currents observed in the Strait in January 1985 (Figure 11) result from winds east of the Philippines pushing water into the Sulawesi Sea increasing the transport through the Makassar Strait and then in turn through the Lombok Strait.

We have also investigated the north-south component of the wind stress north of the Strait as a possible local driving force, but its seasonal cycle varies from only -.01 m/m^2 in February to .035 m/m^2 in August. This local northward wind stress maximum in August is 180° out of phase with the observed southward maximum in the transport emphasizing its lack of importance in the mechanics of the throughflow.

8. Summary and Conclusions

Observation of thermohaline properties in the Lombok Strait and adjacent waters in the Flores Sea and Indian Ocean are combined with current observations and numerical modeling results to obtain an understanding of the low frequency circulation in the Strait. A global reduced gravity model with an active upper layer predicts mean annual sea levels 15-20 cm higher at the northern (Pacific) entrances to the Indonesian archipelago than in the Indian Ocean south of the archipelago. This provides a mechanism for an annual mean transport through the archipelago straits. Consistent with this idea we traced core layers of the Northern Subtropical Central Water and the North Pacific Intermediate Water moving at the 150 m and 300 m depth levels, respectively, southward from the Makassar Strait across the Flores Sea into the Lombok Strait. Their identity is destroyed by intense turbulent mixing associated with 3-4 m/sec tidal currents over the steep sill at the south end of the Strait. Distributions of temperature, salinity, and density on isobaric surfaces indicate a strong persistent flow through the Lombok Strait which forms distinct thermal and haline plumes upon outflow into the Indian Ocean. Maps of surface dynamic height (0/500 db) in the Strait also indicate a strong southward flow with a 10-15 dyn. cm drop between the north and south entrances. Geostrophic velocities in the Strait are far too large suggesting more complex dynamics in the cross-strait momentum balance of such low latitude straits that are much smaller than the internal radius of deformation.

Current measurements on the sill exceeded 3-4 m/sec rendering monitoring there extremely difficult. Moorings in the north Strait, however, allowed identification of the important variability in the low frequency currents. A southward flow concentrated in the upper 200 m of water persists throughout the year. There is a sustained maximum in July through September when speeds exceed 70 cm/sec and a period of weak currents from mid-October through January 1986. During the Timor Sea cyclone season strong westerly winds apparently elevate the sea surface south of the archipelago and force strong northward flow reversals which can persist for ten days.

Simulations from the wind forced numerical model, although of a coarser scale than our observations, reproduce the major cyclone-produced flow events. Additionally, the model simulations clearly identify the strong persistent westward wind stresses in the Timor Sea during the southeast monsoon as the primary cause for the maximum flow phase in the Strait during the months of the northern summer.

We will conclude with a brief discussion relating the Lombok transport to the long-term net throughflow. The combinations of observations and numerical simulations suggest that the Lombok Strait is a major passage of Pacific water into the Indian Ocean. The long-term (1980-1987) net Indonesian throughflow for the model simulations forced by the ECMWF winds is 4.5 Sv. There is now evidence indicating that the present parameterization of wind stress from the ECMWF winds leads to low wind stress estimates. Numerical simulation forced by the Hellerman and Rosenstein (1983) climatological winds suggest that the mean net throughflow may be 7-8 Sv. Extrapolating the Lombok Strait transport observations to the Timor Passages based only on cross-sectional area above 200 m suggests a net throughflow of 10-12 Sv. Hence, in the mean, the flow through Lombok Strait may be approximately 25 percent of the Pacific and Indian Ocean transport. Seasonal and interannual variations may increase this percentage considerably.

Acknowledgement: This work was supported by the Office of Naval Research, Coastal Sciences Program.

References

Bryden, H. L. and Stommel, H. L. (1984) Limiting processes that determine basic features of the circulation in the Mediterranean Sea, Oceanologica Acta, v. 7, pp. 289-296.

Conlon, D. M. (1981) Dynamics of flow in the region of the Tsugaru Strait, Tech. Rept. No. 312, Coastal Studies Institute, Louisiana State University, Baton Rouge, LA.

Garrett, C. and Petrie, B. (1981) Dynamical aspects of the flow through the Strait of Belle Isle, J. Phys. Oceanogr. v. 11, pp. 376-393.

Gordon, A. L. (1986) Interocean exchange of thermocline water, J. Geophys. Res., v. 91, pp. 5037-5046.

Hellerman, S. and Rosenstein, M. (1983) Normal monthly wind stress over the ocean with error estimates, J. Phys. Oceanogr., v. 13, (7), pp. 1093-1104.

Kinder, T. H. and Parrilla, G. (1987) Yes, some of the Mediterranean outflow does come from great depth, J. Geophys. Res., v. 92, pp. 2901-2906.

Kindle, J. C., Hurlburt, H. E., and Metzger, E. J. (1989) On the seasonal and interannual variability of the Pacific to Indian throughflow, Proc. TOGA-COARE Symposium, Noumea, New Caledonia, ORSTOM, Noumea.

Kuuse, J. (1985) The Australian tropical cyclone season 1984-1985, Aust. Met. Mag., v. 33, pp. 129-143.

Lee, T. N., F. Schott, and R. Zantropp (1985) Florida Current: Low frequency variability as observed with moored current meters during April 1982 to June 1983, Science, v. 227, pp. 298-301.

Levitus, S. (1982) Climatological atlas of the world ocean, NOAA Prof. Paper 13, U.S. Department of Commerce, Washington, D.C.

Lukas, R. (1988) Hydrographic observations of the Mindanao Current during WEPOCS III, EOS, v. 69, pp. 1227 (abs.).

McBride, J. L. and Keenan, T. D. (1982) Climatology of the tropical cyclone genesis in the Australian region. J. Climatology, v. 2, pp. 13-33.

Murray, S. P. and Arief, D. (1988) Throughflow into the Indian Ocean through the Lombok Strait, January 1985-January 1986, Nature, v. 333, pp. 444-447.

Richardson, P. L. and Collins, C. A. (1988) Preliminary results from WEPOCS drifters, EOS, v. 69, p. 1227 (abs.).

Toole, J. M. and Raymer, M. E. (1985) Heat and fresh water budget of the Indian Ocean-revisited, Deep Sea Research, v. 32, pp.917-928.

Wyrtki, K. (1961) Physical oceanography of the southeast Asian waters, NAGA Report Volume 2, Scripps Institution of Oceanography, La Jolla.

Wyrtki, K. (1987) Indonesian throughflow and the associated pressure gradient, J. Geophys. Res., v. 92, pp. 12941-2946.